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FRACTURE TOUGHNESS OF H-11 STEEL AND ITS SUSCEPTIBILITY TO STRESS CORROSION CRACKING

By

Kenneth M. Kroupa

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Metallurgy and Materials Science

Lehigh University

1973

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

April 16, 1973
Date

Professor in Charge

G. P. Conard II

Chairman of the Department
of Metallurgy
and Materials Science

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF TABLES

ABSTRACT

The plane strain fracture toughness, K_{Ic}, was measured for H-11 steel using compact tension specimens after two separate heat treatments; one to provide good mechanical properties for normal engineering applications, Rc 46, 195 ksi yield strength, and the other heat treatment to provide maximum strength, Rc 56, 245 ksi yield strength.

The valid K_{Ic} for the Rc 46 specimens averaged 82.0 ksi $\sqrt{in}$ with a high value of 86.8 ksi $\sqrt{in}$ and a low value of 73.9 ksi $\sqrt{in}$. The valid K_{Ic} for the Rc 56 specimens averaged 25.3 ksi $\sqrt{in}$ with a high value of 26.6 ksi $\sqrt{in}$ and a low value of 23.8 ksi $\sqrt{in}$.

The Rc 46 samples exhibited no subcritical crack growth in either steam distilled water or hydraulic oil at K_I levels approaching 95% of the specimens' K_{Ic} with times exceeding 20 hours.

The Rc 56 samples under constant displacement loading exhibited subcritical crack growth in steam distilled water with a measured K_{Iscc} of 17.8 ksi $\sqrt{in}$. The specimens were subjected to the environment just prior to loading, subcritical crack growth commenced without an incubation period, and both the K_I and crack growth increased with time. No subcritical crack growth was encountered in hydraulic oil at K_I levels approaching 98% of the specimens' K_{Ic} with times exceeding 24 hours.

I. INTRODUCTION

A. History of Fracture Mechanics

Prior to an understanding of fracture mechanics, materials were used based upon conventional stress analysis. Structural members were designed incorporating safety factors which resulted in thicker cross sections than the maximum strength of the material warranted. The fracture mechanics concept of stress intensity factors shows that in general higher strength materials have lower fracture toughnesses. Also, increasing the thickness of a specimen may actually change its failure mechanism from the more crack resistant plane stress condition to the much more fracture prone plane strain condition. Failure in plane strain is a brittle fracture which is the development of a running crack at stress levels below the yield strength of the material. Since ultra-high-strength materials are being used to a greater extent than ever before, designers must use stress intensity factors which relate both stress and crack lengths.

A historical review of fracture mechanics is well documented by Weiss and Yukawa.[1] Basically, the study of fracture mechanics was first initiated in 1920 with Griffith's theory of crack propagation.[2] This theory dictates the relationship between fracture strength and defect size for perfectly brittle materials and was verified for glass. Griffith's theory was not applied to the brittle fracture of metallic materials until 1944 by Zener and

Hollomon.[3] In 1957 Irwin introduced the stress intensity approach which predicts fracture when a critical stress distribution, characteristic of the material, is reached.[4]

B. Stress Intensity Factor

The stress intensity factor, K_c, is a material toughness characteristic depending on thickness that reflects the redistribution of stress in a body due to the introduction of a crack. The level of stress intensity applied to the specimen is depicted by the mathematical quantity K_I which relates the applied load and crack length. If the K_I reaches the K_c of a specimen with a sharp crack, the specimen fails catastrophically. The K_c of the specimen decreases with increased material thickness until a minimum stress intensity factor, K_{Ic} is reached. K_{Ic} is a basic material property since it is the lower limit of effective toughness with increase in the degree of constraint to plastic deformation. It can be defined in terms of load and crack length for which the first significant crack growth occurs. K_{Ic} can adequately be described using linear elasticity theory in the plane strain region as long as the plastic zone is small compared to the crack length and the net remaining cross section.

C. Subcritical Crack Growth

Subcritical crack growth can occur within a high strength member by stress corrosion, fatigue, or merely static load. The latter case is usually not considered in design analysis due to the low rate of propagation. The rate of subcritical crack growth may limit the operating stress and life of the structure. Failure of structural elements may progress by subcritical crack growth from some pre-existing crack until the critical crack length for the existing stress is reached and catastrophic fracture occurs. If the environment is corrosive to the material, subcritical crack growth will occur as long as the applied stress intensity level, K_I, is above an environmental threshold, K_{Iscc}. K_{Iscc} is defined as the maximum initial K_I for which no measurable subcritical crack growth occurs over some arbitrary time limit.

D. Objectives

The objectives of this work were:

1. Determine the valid K_{Ic} for H-11 steel heat treated to two different hardnesses; one hardness, Rc 46, representative of good mechanical properties for normal engineering applications and the other hardness, Rc 56, representative of maximum strength.
2. Determine the subcritical crack growth of H-11 steel samples heat treated to Rc 46 and Rc 56 in steam distilled water and in hydraulic oil with the environment introduced prior to a constant displacement loading.

II. EXPERIMENTAL PROCEDURE

A. Sample Specifications

The samples were compact tension specimens machined from two inch diameter bar stock of air melted H-11 steel (AISI designation for Vascojet 1000). Its nominal composition was .40% C, 5.00% Cr, 1.30% Mo, and .50% V.[5] All the samples were machined from the same bar of steel in a T-T orientation. See Figure 1 for an explanation of the orientation and Figures 2 and 3 for the specimen geometry. All dimensions were within the limits set by ASTM for valid compact tension specimens.[6]

The specimens were heat treated in a Leitz tube furnace with the temperature monitored by a Leeds and Northrup millivolt potentiometer using a Chromel versus Alumel thermocouple. The specimens were heat treated in three separate groups using the following heat treatment:

1. Preheat at 1450°F in dry argon for 0.5 hour.
2. Austenitize at 1850°F in dry argon for 1.5 hours.
3. Air cool to 100-150°F.
4. Temper at 1100°F in air for 2.5 hours.
5. Air cool to below 200°F.
6. Repeat tempering process, steps 4 and 5.

This heat treatment produced an average hardness of Rockwell C 46.

Following fatigue cracking, half of the specimens were re-heat treated in two separate groups to Rc 56. The austenitizing phase of the following heat treatment should have eliminated any residual stresses encountered during fatiguing of the samples.

1. Preheat at 1450°F in dry argon for 0.5 hour.
2. Austenitize at 1850°F in dry argon for 1.5 hours.
3. Dry argon cool to 100-150°F.
4. Temper at 970°F in dry argon for 2.5 hours.
5. Dry argon cool to below 200°F.
6. Repeat tempering process, steps 4 and 5.

The hardness readings were taken from an average of four Rockwell C readings on each sample and were used to estimate yield strengths[5] (see Figure 4) which were subsequently required to calculate the plastic zone sizes. The angle of the chevron, measured from the plane normal to the crack growth front, and the notch diameter were measured with an optical comparator, see Table 1 for the measurements.

B. <u>Fatigue Cracking</u>

The samples were fatigue cracked in accordance with ASTM requirements[6] on an MTS System Corporation testing machine using a negative haversine wave at a frequency of twenty cycles per second. The load range was 130-2000 pounds tension-tension with 130-1300 pounds tension-tension for a minimum of the final 2.5% of the crack length. This final load range provided a maximum K_I level of 22. ksi $\sqrt{in}$. The crack growth was monitored with a 10X microscope attached to a micrometer controlled support. The final crack length was grown to approximately one half the effective specimen length, W.

C. Fracturing Specimens

An Instron testing machine with a 10,000 pound load cell was used to stress the specimens at a cross head speed of .02 inch per minute. A load displacement curve was plotted by a Hewlett Packard model 7000A X-Y recorder by obtaining the load output from the Instron using external jacks. Using the one millivolt per inch scale on the Y-axis of the recorder, the load was calibrated to 600 pounds per inch for the Rc 46 specimens and 400 pounds per inch for the Rc 56 specimens. The displacement was measured using an Instron crack opening displacement (COD) gauge, .2 inch gauge length, model number A384-1C. This gauge clipped into the notches machined into each specimen. Two volts ± .01 were supplied to the COD gauge by a Deltron voltage source monitored by a Nonlinear Systems digital voltmeter. Using the .1 millivolt per inch scale on the X-axis of the recorder, the displacement was calibrated to .0025 inch per inch for the Rc 46 specimens and .0015 inch per inch for the Rc 56 specimens. The COD gauge was calibrated using a high magnification Instron extensometer calibrator.

For the stress corrosion tests an open topped polyethylene container was sealed around the bottom of the lower clevis.

The clevis as well as the pins were fabricated from Vascomax 350. The COD gauge was protected by a polyethylene bag which was replaced each time the gauge was removed to prevent possible punctures caused by the sharp edges of the gauge. The environment, either steam distilled water from Electrified Water Company or Mobil DT-E24 hydraulic oil was added to the container until it covered the crack opening of the specimen. As soon as the crack was covered, the load was increased until the desired initial intensity was reached. Constant displacement was then maintained and stress corrosion times were measured on the Instron chart recorder traveling at .2 inch per minute.

D. Analysis of Data

Fatigue cracks, stress corrosion cracks, and specimen dimensions were measured to the nearest .00001 using a toolmaker's microscope that combined optical magnification with micrometer table movement; see Table 2 for specimen dimensions. Construction on the load displacement curves was performed with drafting equipment as outlined by ASTM[6] for valid K_{Ic} tests.

All calculations and validity tests were performed on an IBM 1130 computer. The stress intensity factors were calculated from the equation[6] pertaining to compact tension specimens:

$$K_{Ic} = \frac{P_Q}{B\sqrt{W}} \left[f(a/W) \right] \qquad (1)$$

where P_Q is the load where significant measurable extension of the crack occurs as indicated by a 5% reduction of the initial slope on the load displacement curve, B is the specimen width, W is the specimen length, and $\underline{a}$ is the crack length. $f(\underline{a}/W)$ is a power series[6] given as:

$$f(a/W) = 29.6(\underline{a}/W)^{1/2} - 185.5(\underline{a}/W)^{3/2} + 655.7\,(\underline{a}/W)^{5/2} - 1017.0(\underline{a}/W)^{7/2} + 638.9\,(\underline{a}/W)^{9/2} \quad (2)$$

K_{Ic} values based on the effective crack length rather than the actual crack length as ASTM designates, were found by increasing the actual crack length by the radius of the plastic zone at the crack tip. This radius, r_y, was found from the approximation:[7]

$$r_y = \frac{K_{Ic}^{2}}{6\,\pi(\sigma_{YS})^2} \quad (3)$$

where σ_{YS} is the estimated yield strength[5] from Figure 4 based on the specimen's Rockwell C hardness. A new approximation for r_y was found each time a variance in K_{Ic} exceeded 1.0 psi.

The equation for K_{Ic} was also used to determine the initial stress intensity level, K_I, for the corrosion tests by using the fatigue crack length for $\underline{a}$ and the initial applied load for P_Q.

III. RESULTS AND DISCUSSION

A. Valid K_{Ic} Tests for Rockwell C 46 H-11 Steel

The Rc 46 samples had an average K_{Ic} of 82.0 ksi $\sqrt{in}$ based on three specimens. The highest value was 86.8 ksi $\sqrt{in}$ and the lowest value was 73.9 ksi $\sqrt{in}$, see Table 3. The experiments met all required validity tests by the American Society of Testing Materials for compact tension specimens.[6] In the calculation of the K_{Ic}, ASTM employs the actual crack length as measured from the sample. For precision the crack length should also include the radius of the plastic zone at the crack tip, r_y. For the plane strain condition, r_y can be approximated by Equation 3. This value added to the actual crack length yields the effective crack length in the specimen. Using the effective crack length rather than the actual crack length to calculate K_{Ic} results in values 2.8% greater.

Valid K_{Ic} values for H-11 steel with the same tempering temperatures were reported by Amateau and Steigerwald[8] as 73.2 ksi $\sqrt{in}$ with a high value of 80.1 ksi $\sqrt{in}$ and a low value of 61.6 ksi $\sqrt{in}$. These values were based on an average of eight notch-bend three-point-loaded tests using one inch square specimens; however, the double tempers were for only two hour durations compared to 2.5 hours for the present work. Amateau and Steigerwald's work was for T-S oriented samples[9] fabricated from plate; whereas, this work is for T-T oriented samples fabricated from rod as shown in Figure 1. T-S oriented specimens[9] have their transverse grain direction normal to the fracture plane and their thickness, the direction of crack propagation in the fracture plane. Growth of cracks in T-S oriented specimens may be aided by the elongated grains thereby accounting for K_{Ic} values 10.8% lower for basically the same material.

The number of samples used to report valid K_{Ic} tests was rather limited; however, of the samples tested for environmentally enhanced subcritical crack growth, those that showed no stress corrosion cracking, see Table 4, yielded valid K_{Ic} values within the limits reported in this paper. All of the values were within a 95% two-sided confidence interval. The author considers these K_{Ic} values valid and also an indicator that no stress corrosion cracking occurred. It is possible that stress corrosion could have increased the crack tip radius formed by fatiguing thereby resulting in a fictitious K_{Ic} larger than the valid K_{Ic}.

B. Valid K_{Ic} Tests for Rockwell C 56 H-11 Steel

The K_{Ic} of the Rc 56 samples was 25.3 ksi $\sqrt{in}$ based on six specimens with a high value of 26.6 ksi $\sqrt{in}$ and a low value of 23.8 ksi $\sqrt{in}$. This data, given in Tables 3 and 4, includes four samples which showed no subcritical crack growth. Using the effective crack length rather than the actual crack length increased the K_{Ic} by only .2%. This is due to the fact that the plastic zone decreases as the stress intensity factor decreases; therefore, the actual crack length approaches the effective crack length. Valid K_{Ic} values for H-11 steel with a triple temper of one hour each at 950°F (Rc ranging from 55 to 56) were reported by Miller[10] as 25.3 ksi $\sqrt{in}$ with a high value of 27.0 ksi $\sqrt{in}$ and a low value of 23.0 ksi $\sqrt{in}$. Miller's samples were center-slotted sheets of T-S orientation[9] with fatigue cracking performed prior to heat treatment. These values compare very closely with those reported in this paper.

As expected the K_{Ic} for the Rc 46 samples was greater than the K_{Ic} for the Rc 56 samples. This is illustrated by the definition of K_{Ic} as a material toughness property that establishes a relationship of critical load and crack length. The initial crack lengths for all the specimens were relatively equal, see Table 2; however, the loads required to fracture the Rc 56 samples, see Tables 3 and 4, were much less than that required to fracture the Rc 46 samples which were of lower strength but tougher. As a result the tougher more crack growth resistant material has the larger K_{Ic} regardless of strength.

C. Stress Corrosion Cracking Tests on Rockwell C 46 H-11 Steel

Subcritical crack growth tests were performed on the Rc 46 samples in both steam distilled water and hydraulic oil, see Table 4. Two specimens, A13 and A16, were tested in water for times exceeding 23 hours at K_I values approaching 93% of their K_{Ic} values. A third sample, A15, was also tested in water;

however, it failed during loading. No measurable subcritical crack growth was encountered as evidenced by no reduction of the applied load, by no movement of the COD gauge calibrated to .0015 inch per inch, and also by optical and scanning electron microscopy. One sample, A14, was tested in hydraulic oil for 20 hours at a K_I level of 95% of its K_{Ic}. Again, no measurable subcritical crack growth was encountered.

D. <u>Stress Corrosion Cracking Tests on Rockwell C 56 H-11 Steel</u>

Subcritical crack growth tests were also performed on the Rc 56 specimens in both steam distilled water and in hydraulic oil. Six specimens were tested in water with subcritical crack growth leading to brittle fracture with initial K_I values equal to or exceeding 71% of their K_{Ic} values, see Table 5. Samples tested in water at initial K_I values below 71% showed no indications of subcritical crack growth with times exceeding 22 hours, see Table 4. To validate the environmentally enhanced subcritical crack growth results, one specimen, A23, was tested in air at a K_I level of 93% of its K_{Ic}. No subcritical crack growth was evidenced during a period of 65 hours.

Figure 5 is the graph of initial K_I versus propagation time to failure in steam distilled water. It indicates the transition from the initial K_I that causes subcritical crack growth leading to failure at a relatively rapid rate to the measured environmental threshold, K_{Iscc}, of 17.8 ksi $\sqrt{in}$

that shows no indication of subcritical crack growth over a 22 hour time interval. The K_{Iscc} of 17.8 ksi $\sqrt{in}$ was based on the fact that sample A30 at a K_I of 17.91 ksi $\sqrt{in}$ failed in steam distilled water after 163 minutes while sample A27 at a K_I of 17.83 ksi $\sqrt{in}$ showed no indications of subcritical crack growth in steam distilled water after 22 hours. Figure 5 shows similar trends to that found by Steigerwald[11] for H-11 steel heat treated to a 295 ksi ultimate strength level using center precracked and T-S oriented specimens[9] subjected to a distilled water environment. However, his samples were tested under a constant load; whereas, the present work involves specimens subjected to constant displacement. This causes the load to decrease as the stress corrosion crack grows although with both types of load the K_I increases with crack growth.

Figure 6 shows a linear relationship of change in load to the change in crack opening displacement for specimens subjected to subcritical crack growth and is representative of all specimens tested. The slopes for all such samples were within 10% of the average slope of -10^5. Figure 7 was obtained by plotting the total changes in final COD at catastrophic failure versus critical crack length due to stress corrosion cracking after subcritical crack growth. The dependence of crack opening displacement on actual stress corrosion crack length can be estimated from Figure 7; therefore, the slope of load to crack growth from Figure 6 was approximated as -2169 pounds per inch. The stress corrosion crack commenced as soon as the initial K_I was applied for all samples exhibiting stress corrosion cracking, thus inferring that no incubation times were encountered. This is shown in Figure 8 for sample A27 where the change in COD and load from Table 6 was plotted against propagation time. The lack of incubation time is most likely a result of the fact that the specimens were saturated by the stress corrosive environment just prior to loading to the initial K_I rather than applying the environment after loading. This environmental condition was used to most accurately represent actual conditions. Figure 9, based on the data from sample A27, emphasizes that K_I and crack growth rate increase with time even though the applied load decreased with increased crack length due to the constant displacement type loading. This is in agreement with Wessel's[12] predictions for compact tension specimens that the K_I increases as the load decreases. Since K_I can be considered as one of the driving forces for environmental cracking, the crack growth rate must increase with time as long as the K_I increases. This relationship of crack growth rate to K_I for sample A27 is shown in Figure 10 to be roughly linear. Johnson and Willner[13] obtained a similar relationship with center-cracked H-11 steel specimens, yield strength 230 ksi, T-S orientation[9], in the presence of water under constant load conditions. Figure 10, based on sample A27, predicts no crack growth below a K_I of 19.3 ksi $\sqrt{in}$. This agrees within 8% of the experimental K_{Iscc} of 17.8 ksi $\sqrt{in}$ previously reported in this paper. This can possibly be an additional method of estimating the K_{Iscc}; however, extrapolation outside the range of experimental data can be misleading. Furthermore, Sheinker and Wood[14] as well as Brown [9] reported three stages where the K_I level has varying effects on the crack growth rate. If the extrapolation crossed into another stage, the estimated K_{Iscc} would be erroneous.

Stress intensity factors were calculated from the six specimens exhibiting subcritical crack growth to determine if valid K_{Ic} values were possible from these results, see Table 5. The actual crack length was measured to the end of the stress corrosion crack and the load at failure was used as P_Q. The assumption that P_Q was the load at failure was deemed justifiable since this proved to be the case for all valid K_{Ic} tests on the Rc 56 specimens. The average K_{Ic} for these six specimens was 27.2 ksi $\sqrt{in}$ or 7.5% higher than the average K_{Ic} previously reported from the valid K_{Ic} tests. The K_{Ic} values for three of the six samples exhibiting stress corrosion cracking failed, all on the maximum side, to be within a 95% 2-sided confidence interval based on the valid K_{Ic} specimens. The increased K_{Ic} value was most likely caused by the bluntness of the crack tip caused by stress corrosion as compared to the sharpness of the fatigue crack. The author feels that the K_{Ic} values obtained from samples exhibiting subcritical crack growth do not provide a good estimate of the valid K_{Ic} and, therefore, should never be treated as such.

The Rc 56 samples were also evaluated for subcritical crack growth in an environment of hydraulic oil, see Table 4. Three specimens were tested at K_I levels approaching 98% of their K_{Ic} values and for times exceeding 24 hours. No indications of subcritical crack growth were present as evidenced by no reduction of the applied load, by no movement of the COD gauge, and by visual inspection.

E. Fracture Surfaces

Figure 11 shows the fracture surface of an Rc 46 specimen subjected to a valid K_{Ic} test. This is identical in appearance to the fracture surface of similar Rc 46 specimens that were subjected to steam distilled water or hydraulic oil for times exceeding 20 hours and at K_I levels approaching 95% of their K_{Ic}. Although a flat crack was obtained in the direction of crack growth, the obliqueness of the sides indicates the material is more ductile than the Rc 56 valid K_{Ic} specimen, Figure 12, where no measurable obliqueness is present. The effect of the hardness differences is more clearly seen from Figures 13 and 14 which are scanning electron microscope photographs of typical areas on the catastrophic fracture surface of Rc 46 and Rc 56 specimens respectively. The catastrophic fracture surface of the Rc 46 specimen is similar to the catastrophic fracture surface of the Rc 56 specimen except that the Rc 46 specimen shows much more ductile dimpling. The higher fracture toughness of the Rc 46 specimens may be explained by this ductile dimpling.

The photograph in Figure 15 shows the fracture surface of an Rc 56 specimen subjected to subcritical crack growth in steam distilled water under constant displacement loading at an initial K_I of 71% of its K_{Ic}. The sketch denotes the three different modes of crack growth across the specimen. Figures 14, 16, and 17 are scanning electron microscope photographs of these three modes and were taken at typical areas on the same specimen as shown in Figure 15. Figures 14, 16, and 17 show the catastrophic fracture surface, the fatigue crack surface, and the stress corrosion crack surface respectively. These three modes of crack growth have been described by Phillips, et. al.[15] for H-11 steel, ultimate strength 270-290 ksi as follows: The fatigue crack surface exhibits distinct fatigue striations surrounded by flat, rubbed appearing zones; the stress corrosion crack surface exhibits a predominantly intergranular mode of rupture with the remaining areas quasi-cleavage; the catastrophic fracture surface exhibits a mixture of quasi-cleavage and dimple rupture. The description of these three modes agree with the present work; however, the fatigue striations were not resolvable due to the small change in

K_I level used for fatigue crack growth.

IV. CONCLUSIONS

The valid K_{Ic} for H-11 steel compact tension specimens, heat treated to Rc 46 and with a T-T orientation, was 82.0 ksi $\sqrt{in}$. The valid K_{Ic} for samples heat treated to Rc 56 was 25.3 ksi $\sqrt{in}$.

The Rc 46 specimens were not susceptible to subcritical crack growth in steam distilled water or Mobil DT-E24 hydraulic oil environments with initial K_I levels approaching 95% of the specimens' K_{Ic} applied for over 20 hours. Specimens which did not exhibit subcritical crack growth yielded statistically valid K_{Ic} values.

The Rc 56 specimens exhibited subcritical crack growth in steam distilled water when initial K_I levels were at or above 71% of their K_{Ic} values. When initial K_I levels were below 71% of their K_{Ic} values, the specimens showed no subcritical crack growth with times exceeding 22 hours. Pertaining to the samples that did exhibit subcritical crack growth under constant displacement loading, no incubation times were noted and both the K_I and crack growth rate increased with time. Valid K_{Ic} estimates cannot be made from specimens exhibiting subcritical crack growth due most likely to blunting of the crack by stress corrosion.

The Rc 56 specimens were not susceptible to subcritical crack growth in Mobil DT-E24 hydraulic oil environments for K_I levels approaching 98% of the specimens' K_{Ic} applied for over 24 hours.

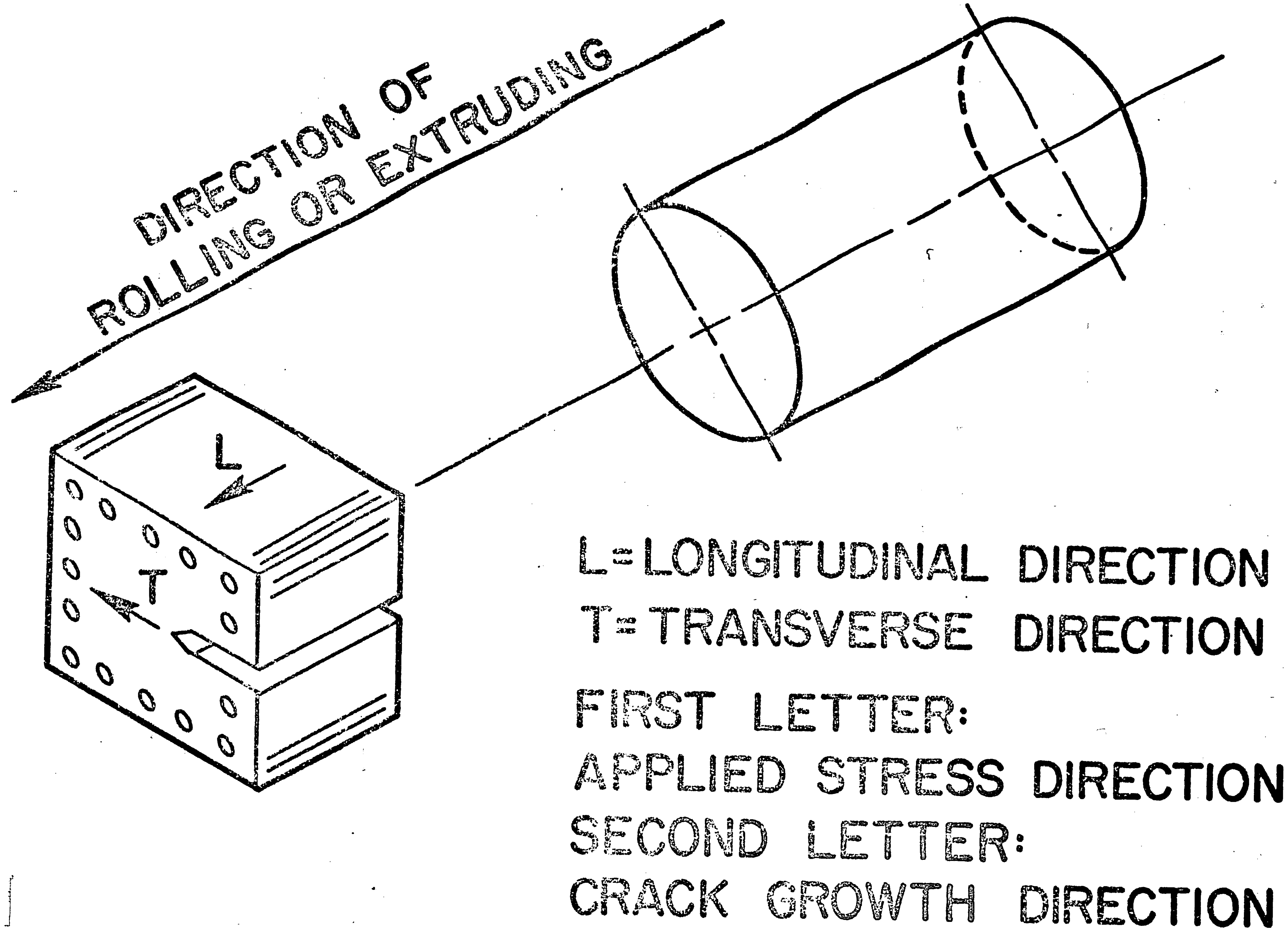
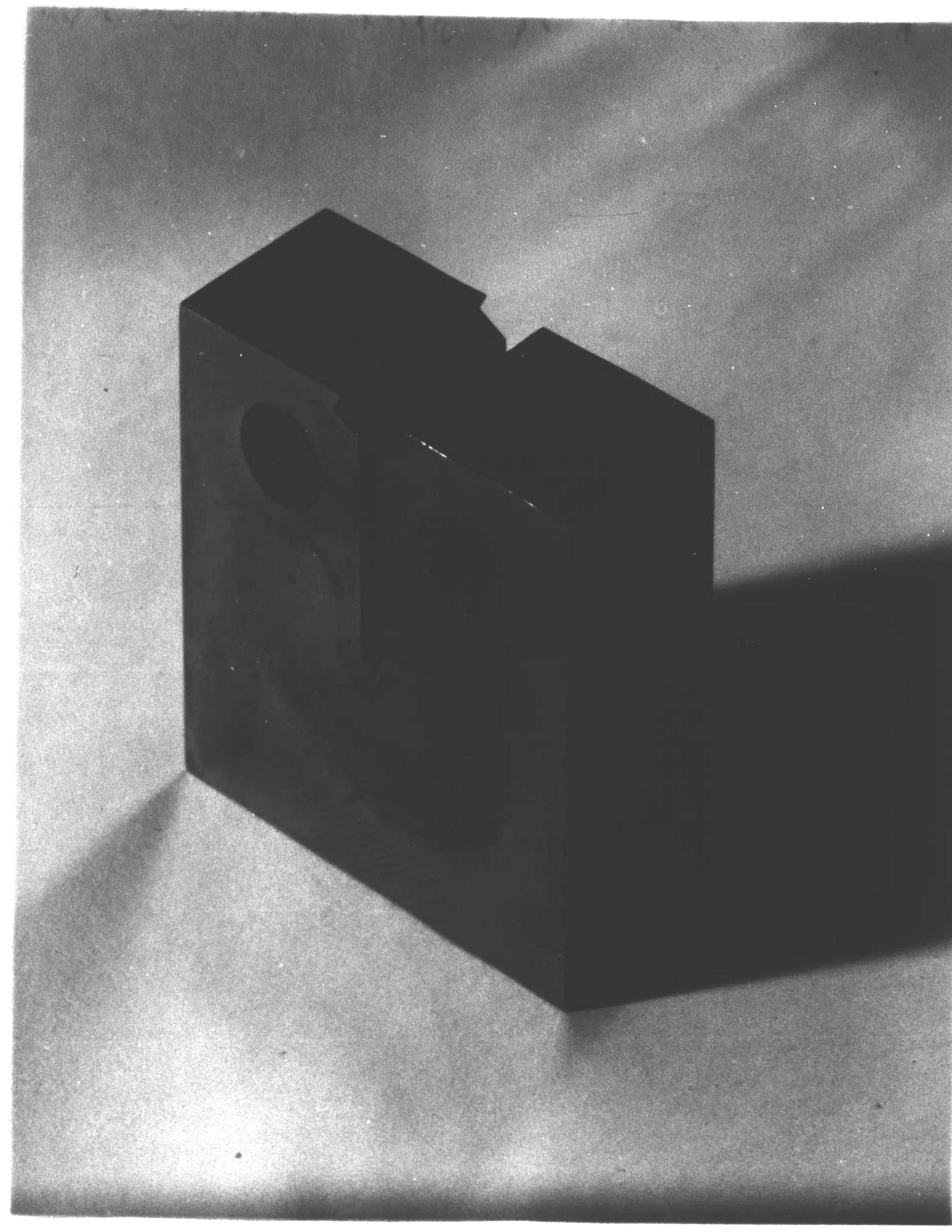


FIG. 1 TWO LETTER ORIENTATION DESIGNATIONS FOR SPECIMENS FABRICATED FROM ROLLED OR EXTRUDED ROD.



APPROXIMATELY 1.2 X

FIG. 2 - H-11 STEEL COMPACT TENSION SPECIMEN.

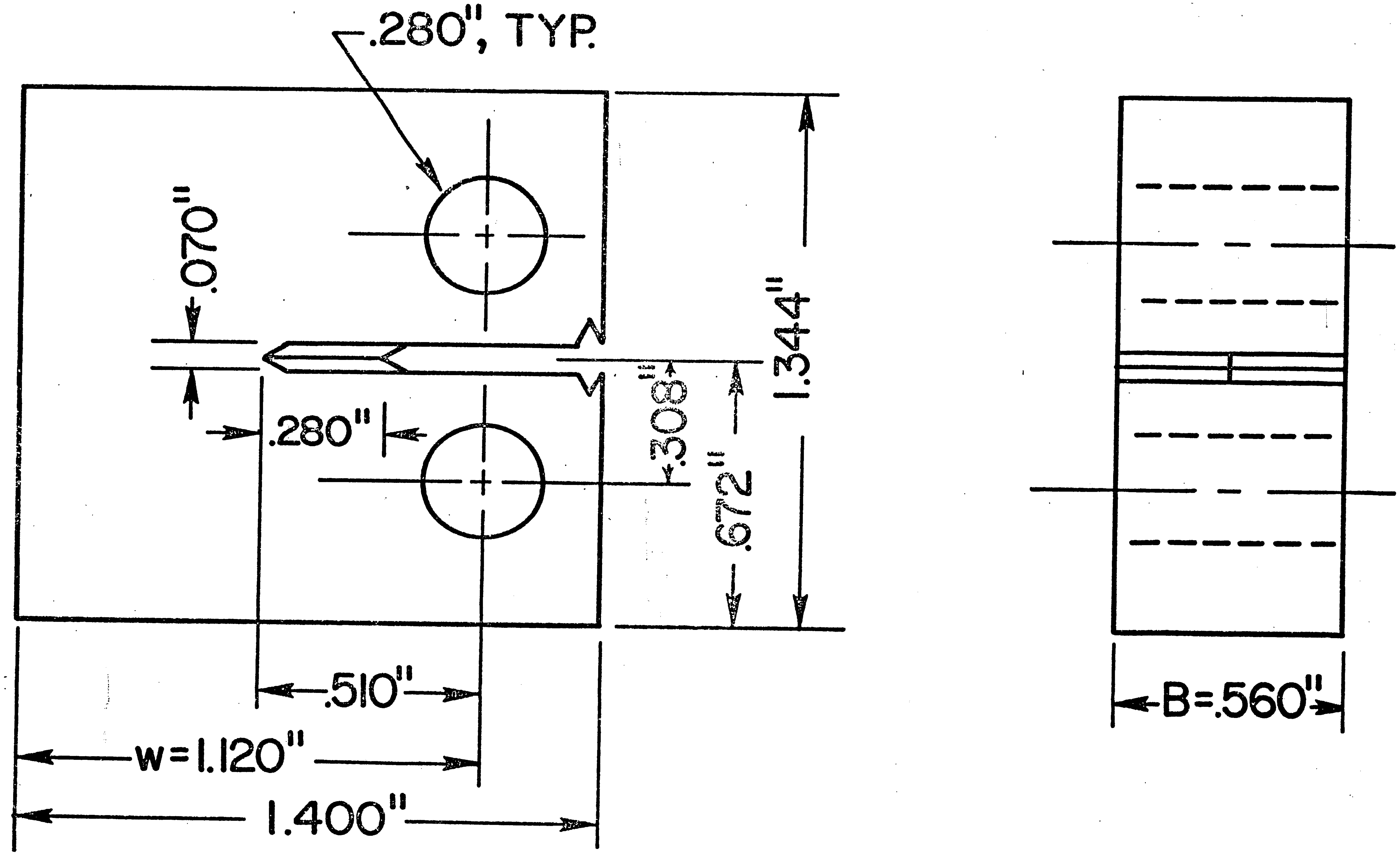


FIG. 3- H-II STEEL COMPACT TENSION SPECIMEN DESIGNED TO ASTM REQUIREMENTS[6]

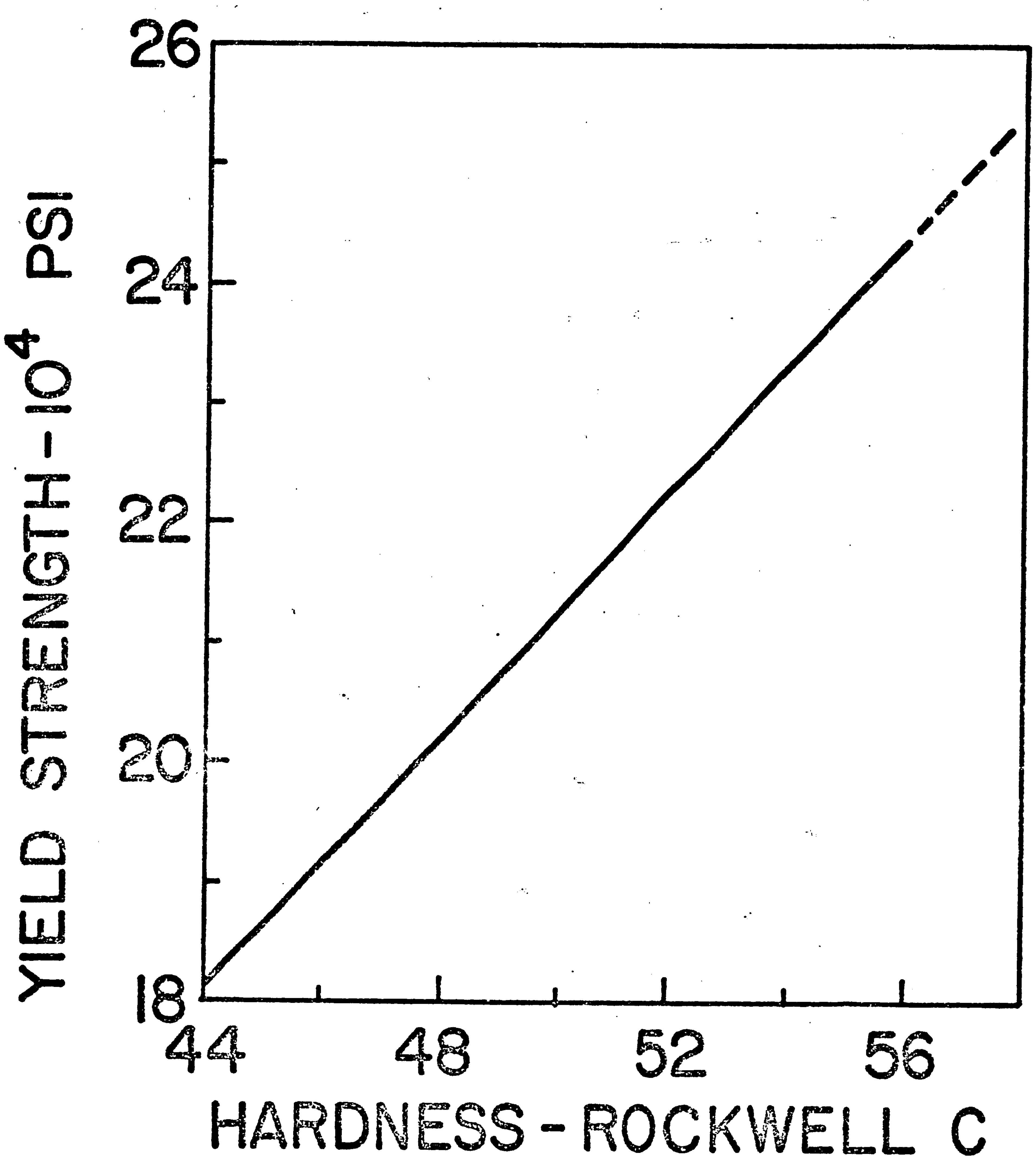


FIG. 4 - CORRELATION OF YIELD STRENGTH TO HARDNESS FOR H-11 STEEL[5]

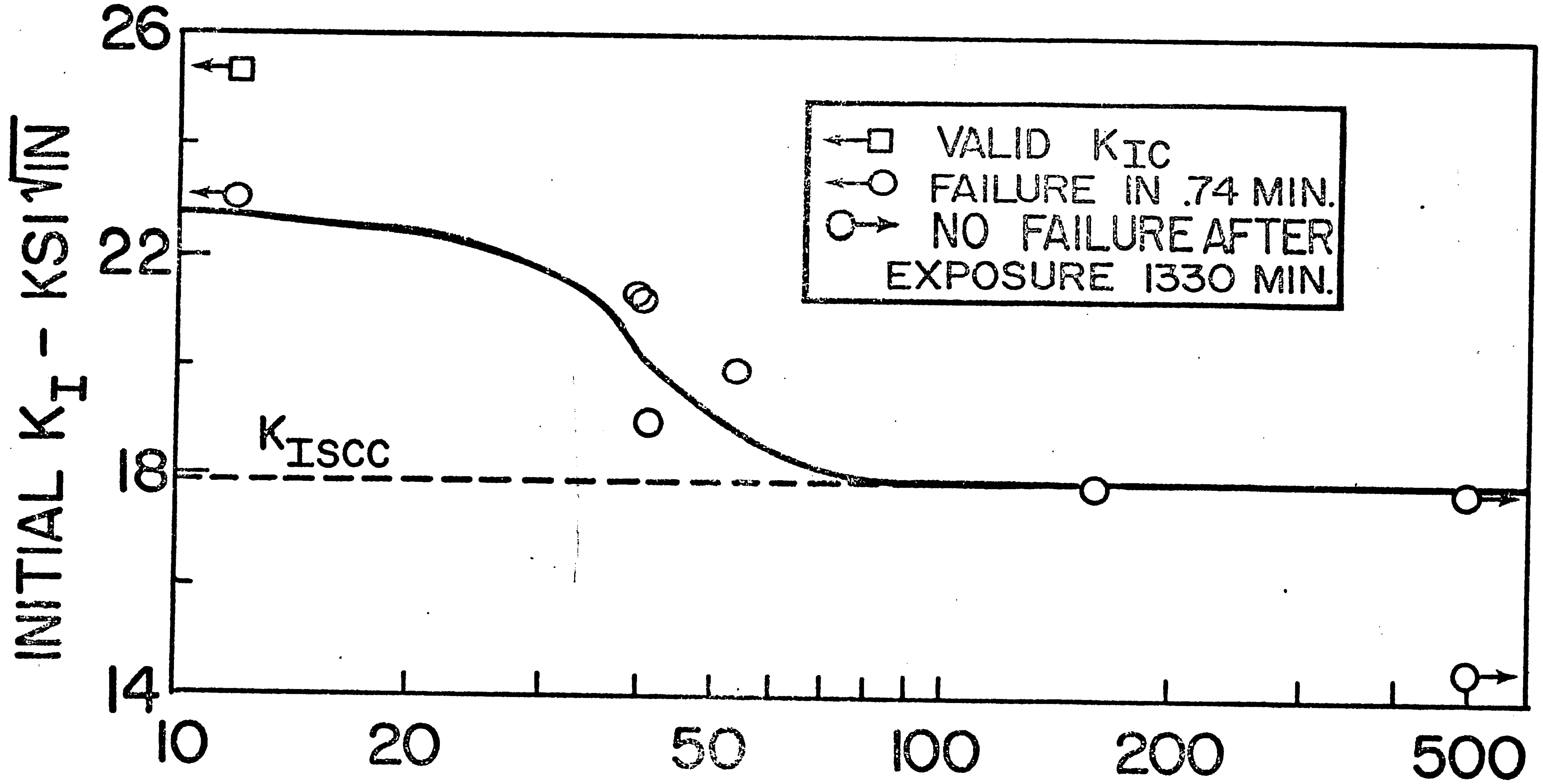


FIG. 5 - STRESS CORROSION FAILURE OF H-11 STEEL, R_C56, IN STEAM DISTILLED WATER UNDER CONSTANT DISPLACEMENT LOADING.

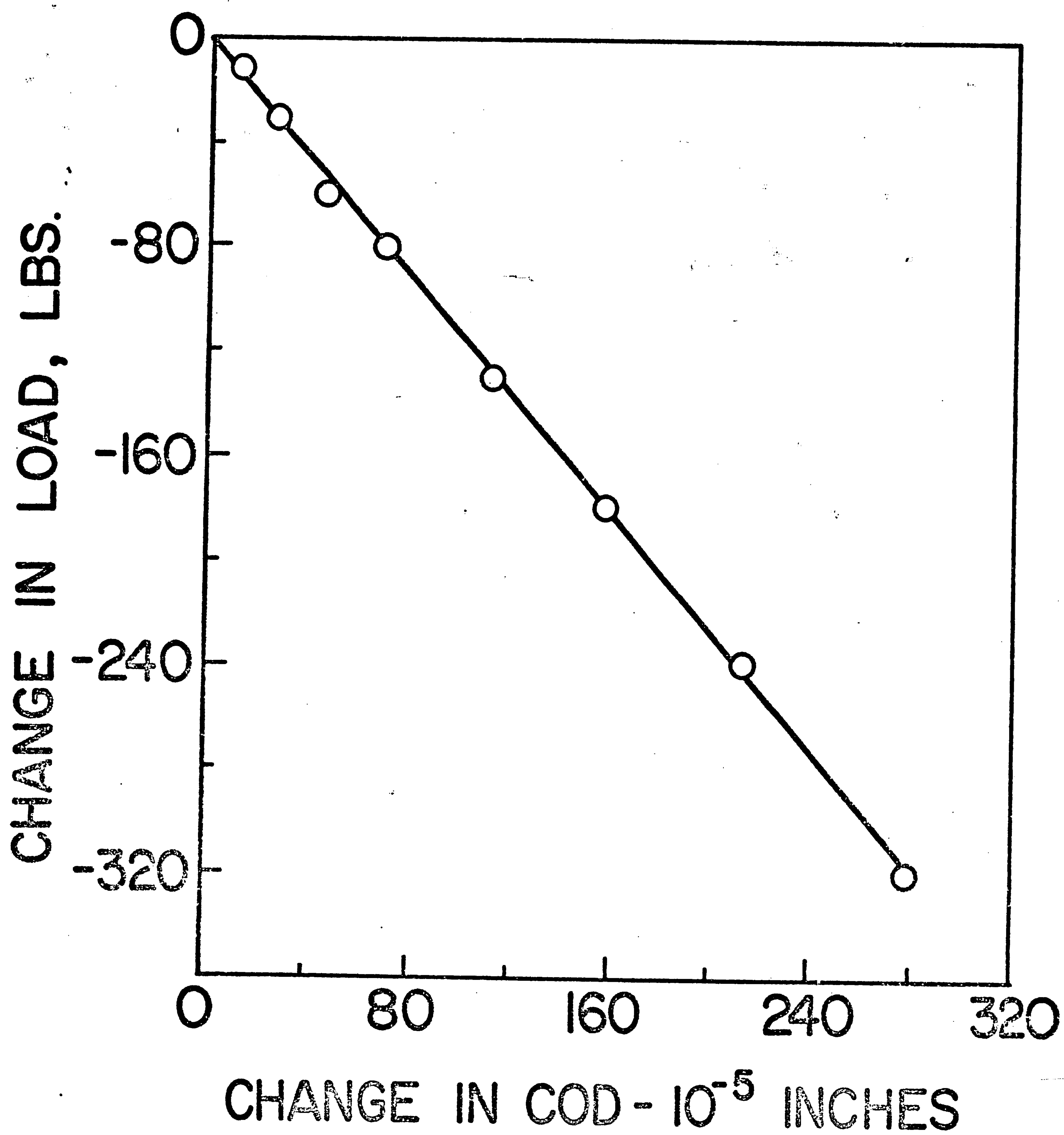


FIG. 6 - RELATIONSHIP OF CHANGE IN LOAD TO CHANGE IN COD FOR STRESS CORROSION CRACKING OF H-11 STEEL, R_C56, IN STEAM DISTILLED WATER.

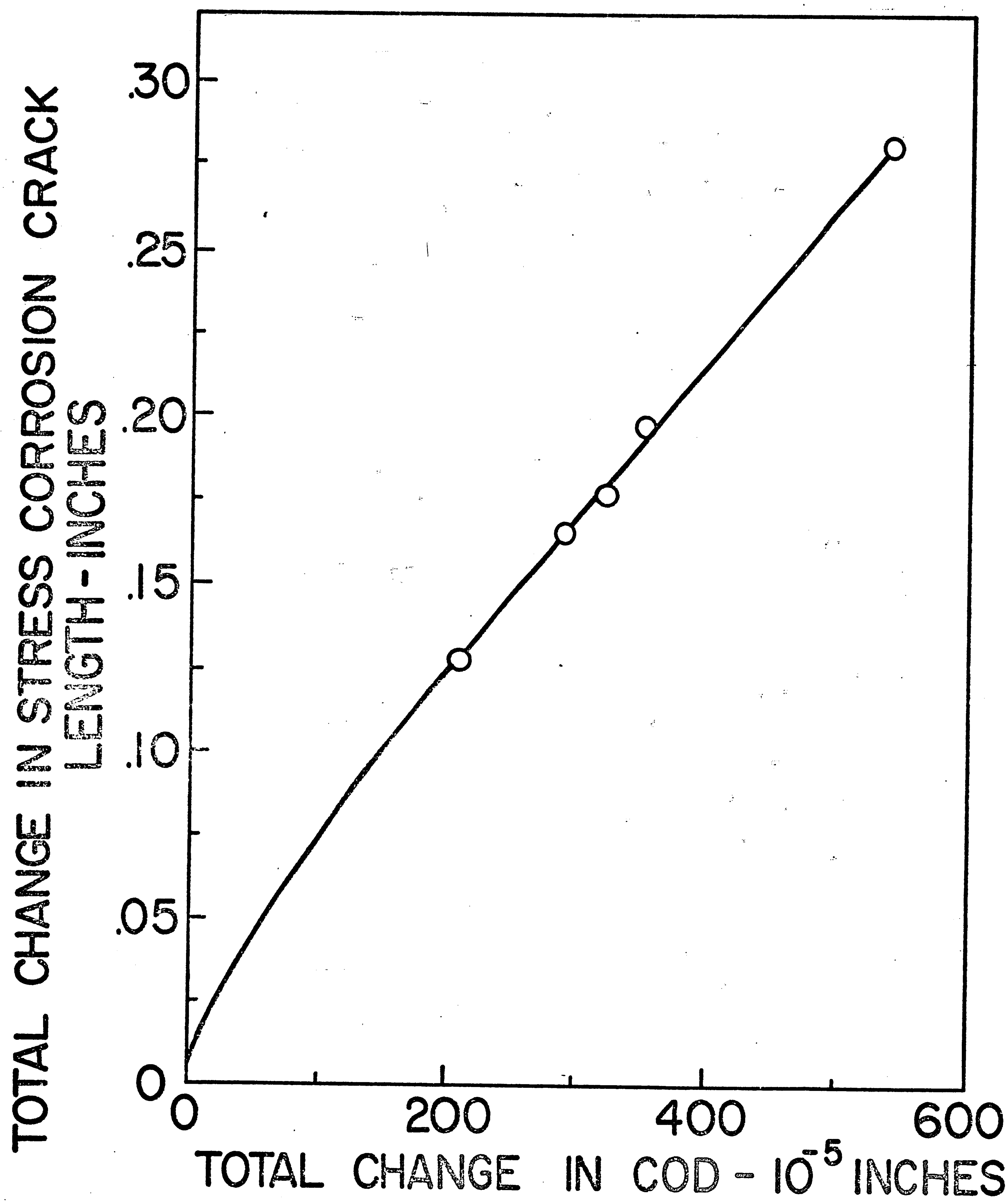


FIG. 7 - EQUIVALENCE OF STRESS CORROSION CRACK LENGTH TO COD.

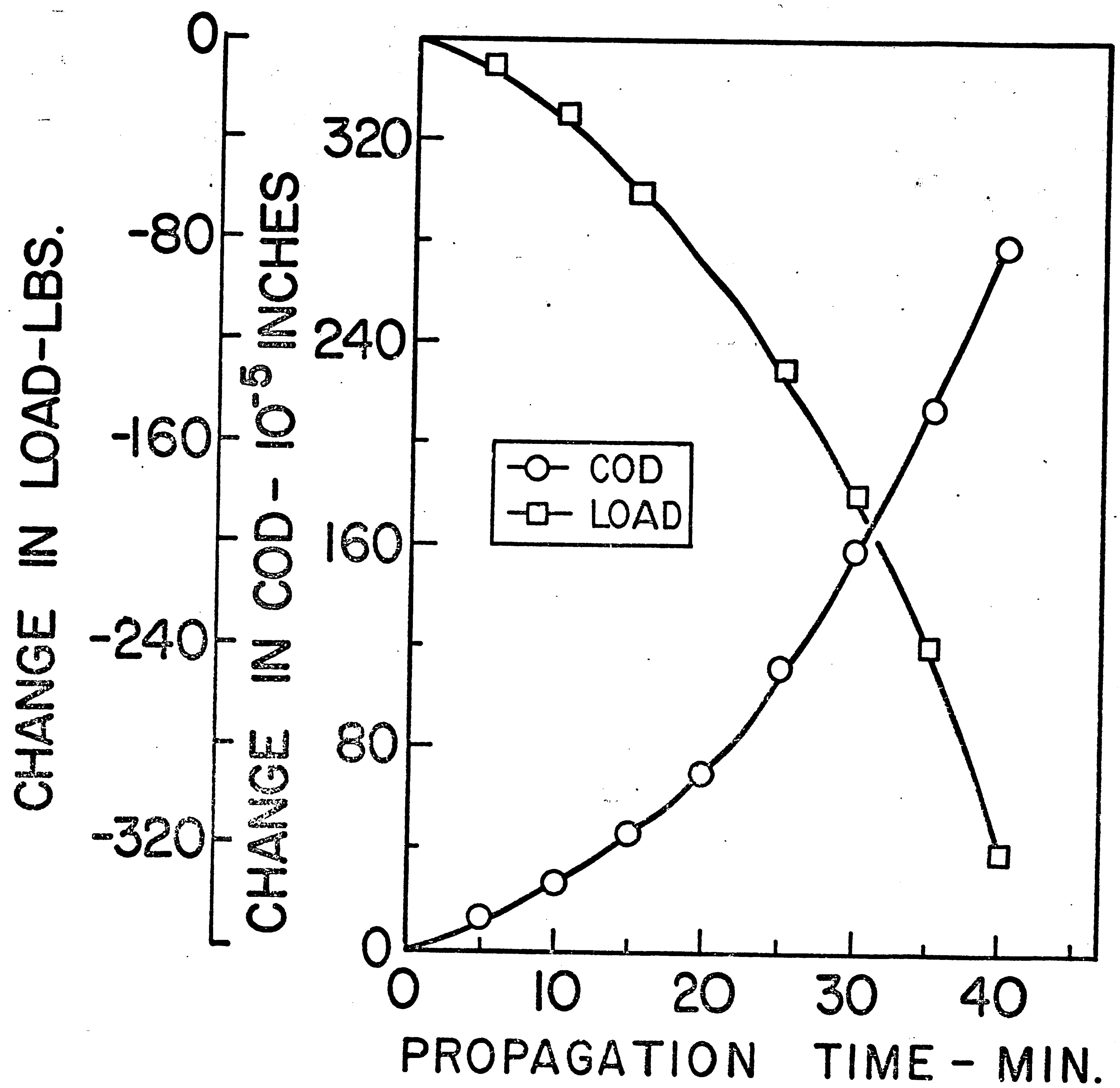


FIG. 8 - TYPICAL SUBCRITICAL CRACK GROWTH OF H-II STEEL, R_c56, IN STEAM DISTILLED WATER.

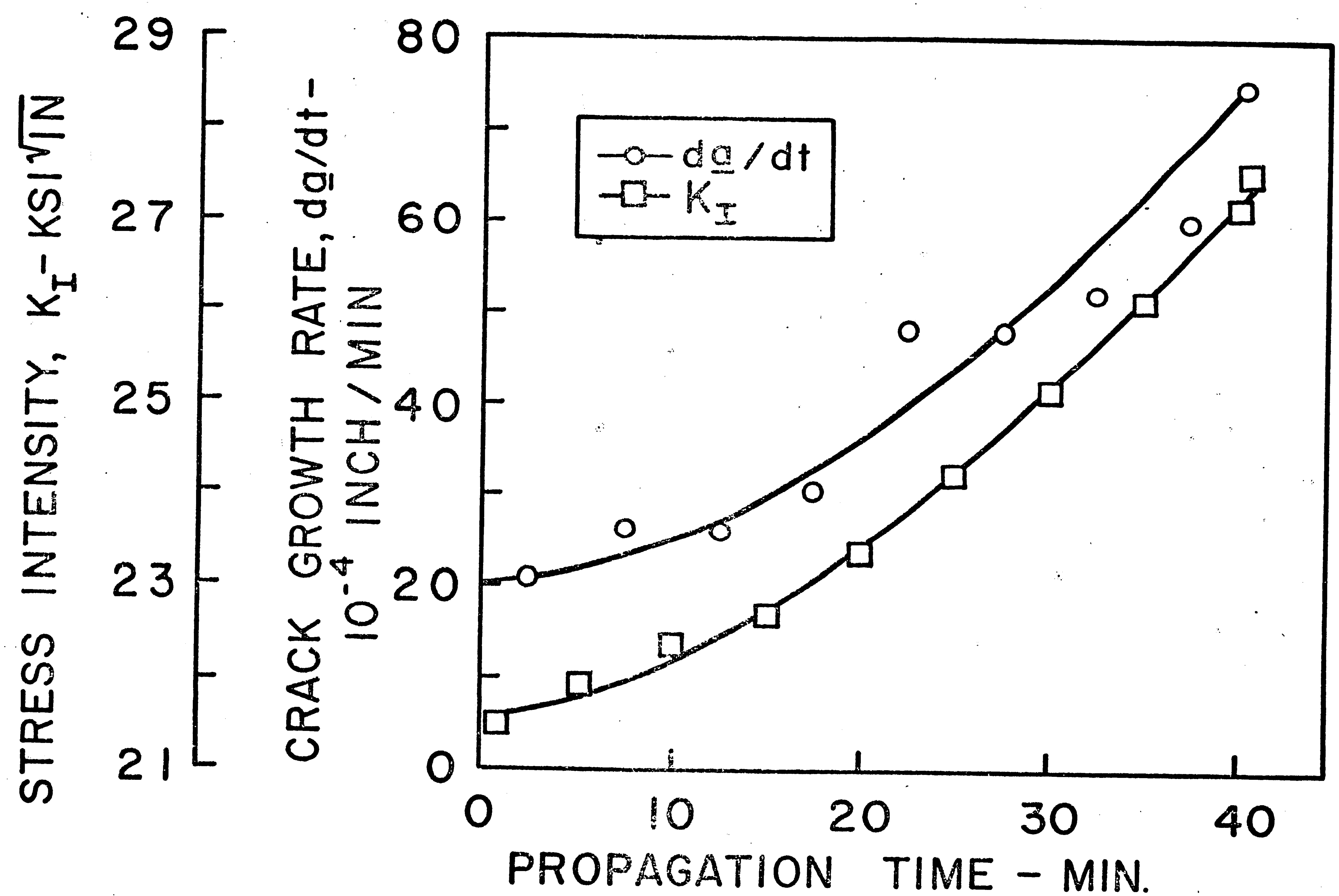


FIG. 9 - TYPICAL INCREASES OF CRACK GROWTH RATE AND K_I WITH TIME FOR H-11 STEEL, R 56 IN STEAM DISTILLED WATER.

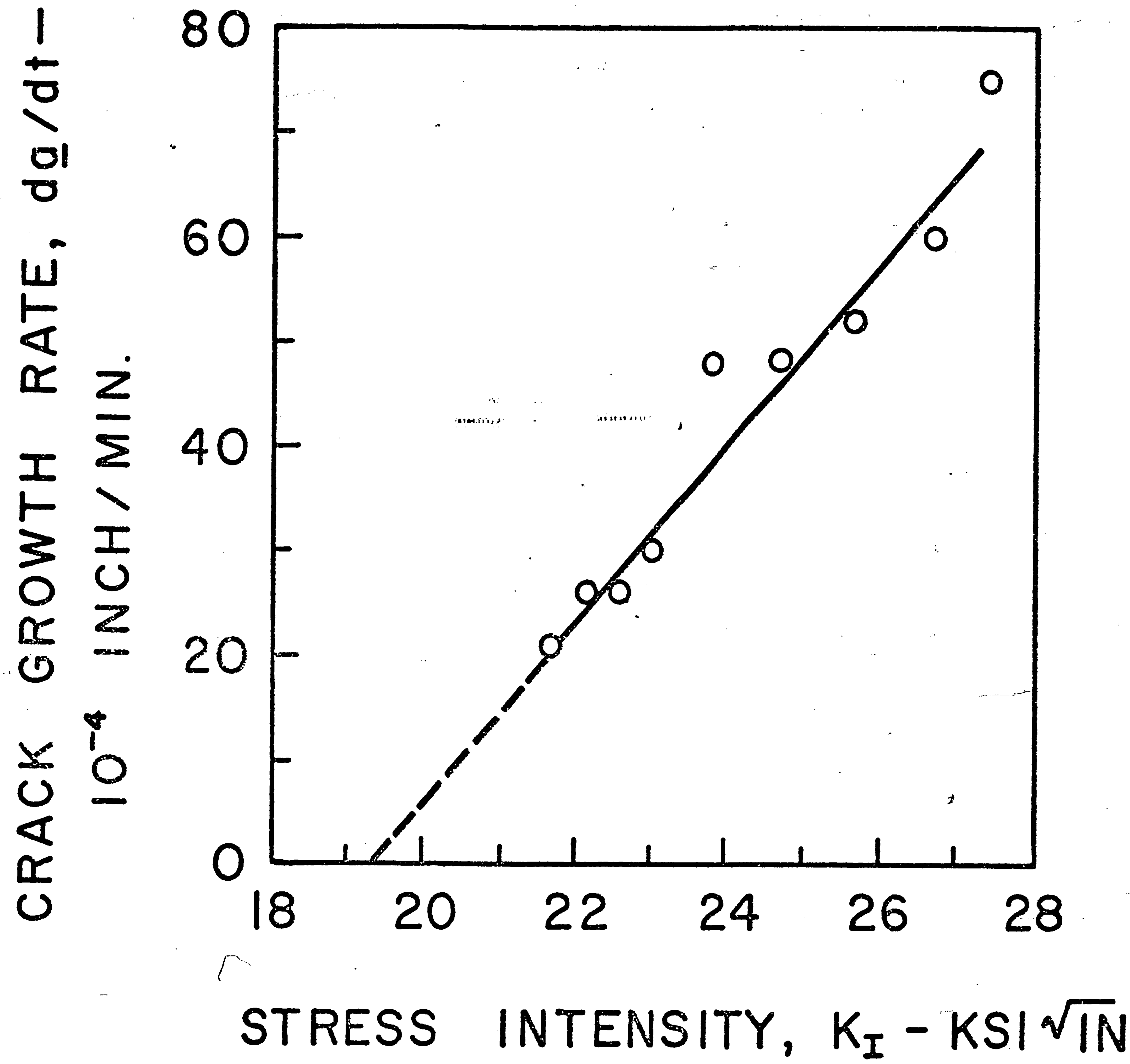
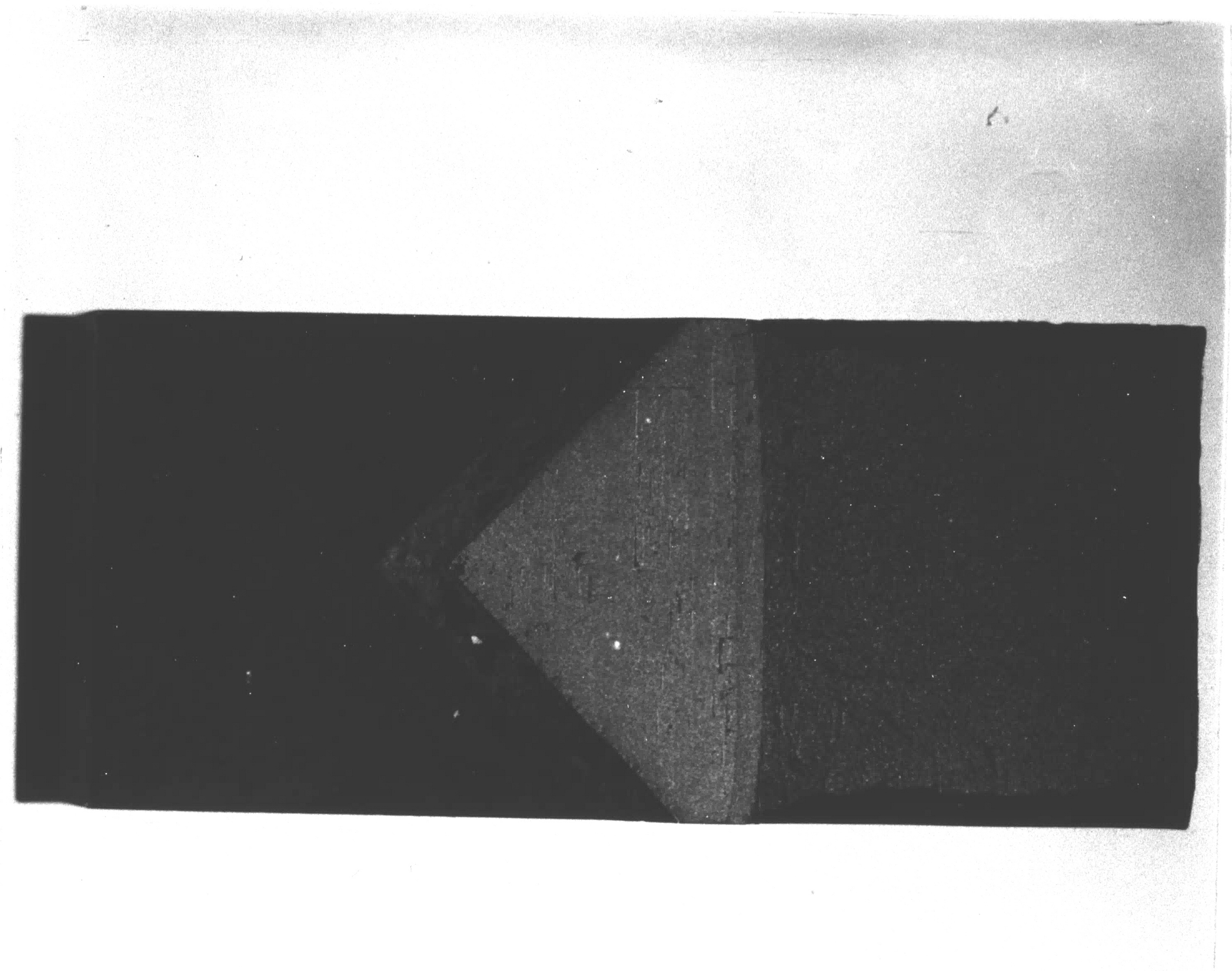


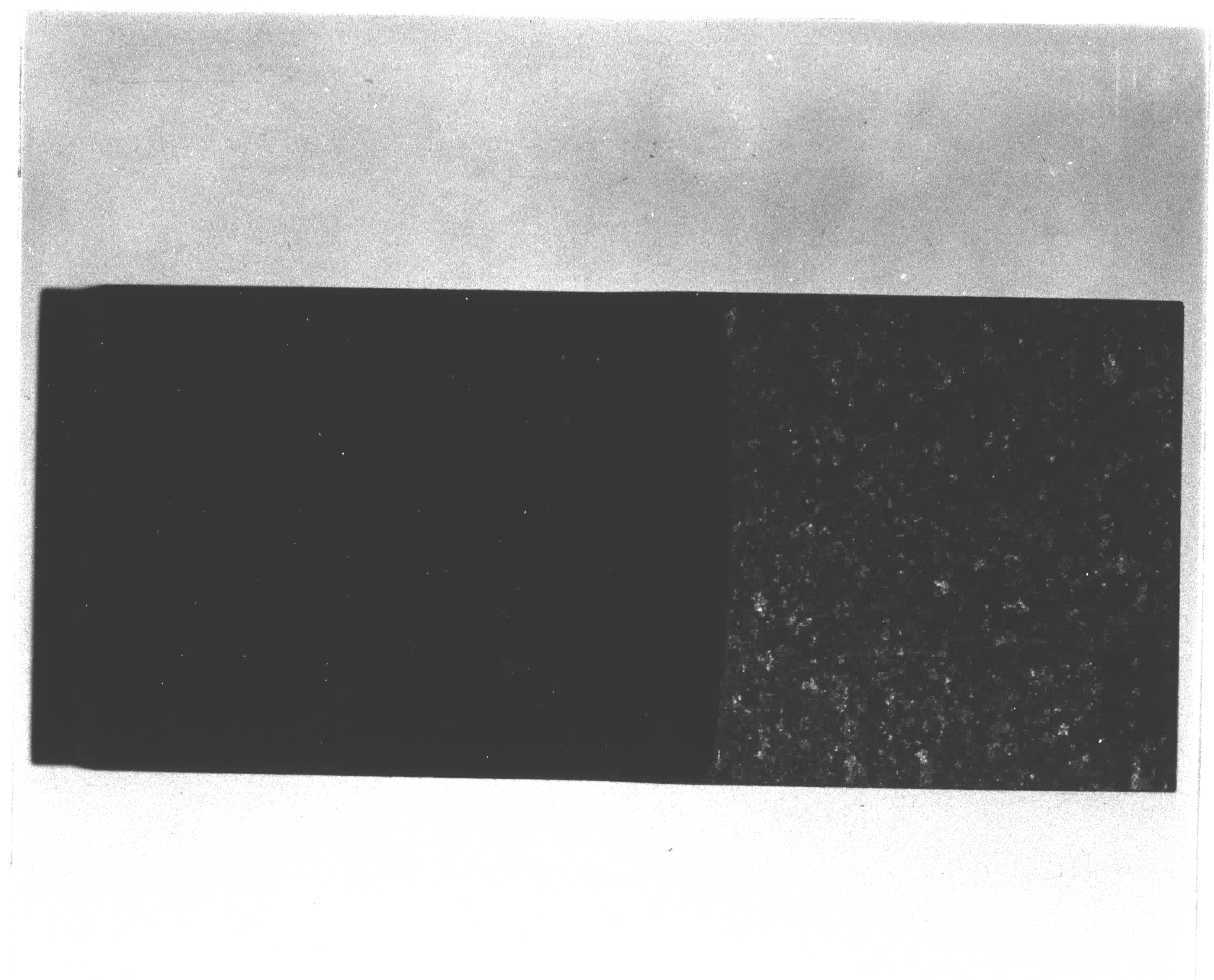
FIG. 10 - TYPICAL RELATIONSHIP OF CRACK GROWTH RATE TO K_I FOR H-11 STEEL, R_C56, IN STEAM DISTILLED WATER.



SAMPLE A11

APPROXIMATELY 3.2 X

FIG. 11 - FRACTURE SURFACE OF A VALID K_{IC} Rc 46, H-11 STEEL SPECIMEN.

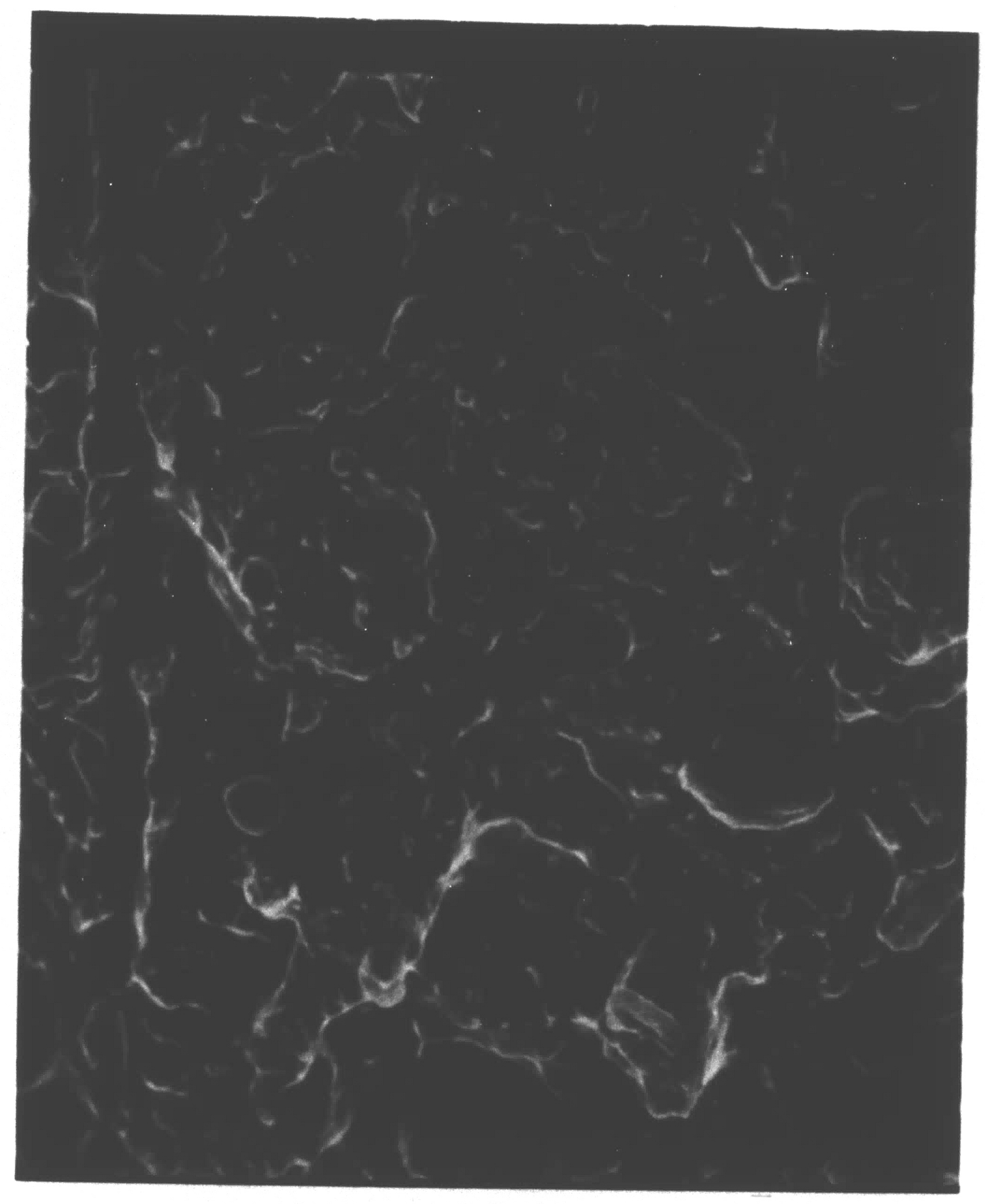


SAMPLE A06

APPROXIMATELY 3.2 X

FIG. 12 - FRACTURE SURFACE OF A VALID K_{IC}
Rc 56, H-11 STEEL SPECIMEN.

CRACK
PROPAGATION



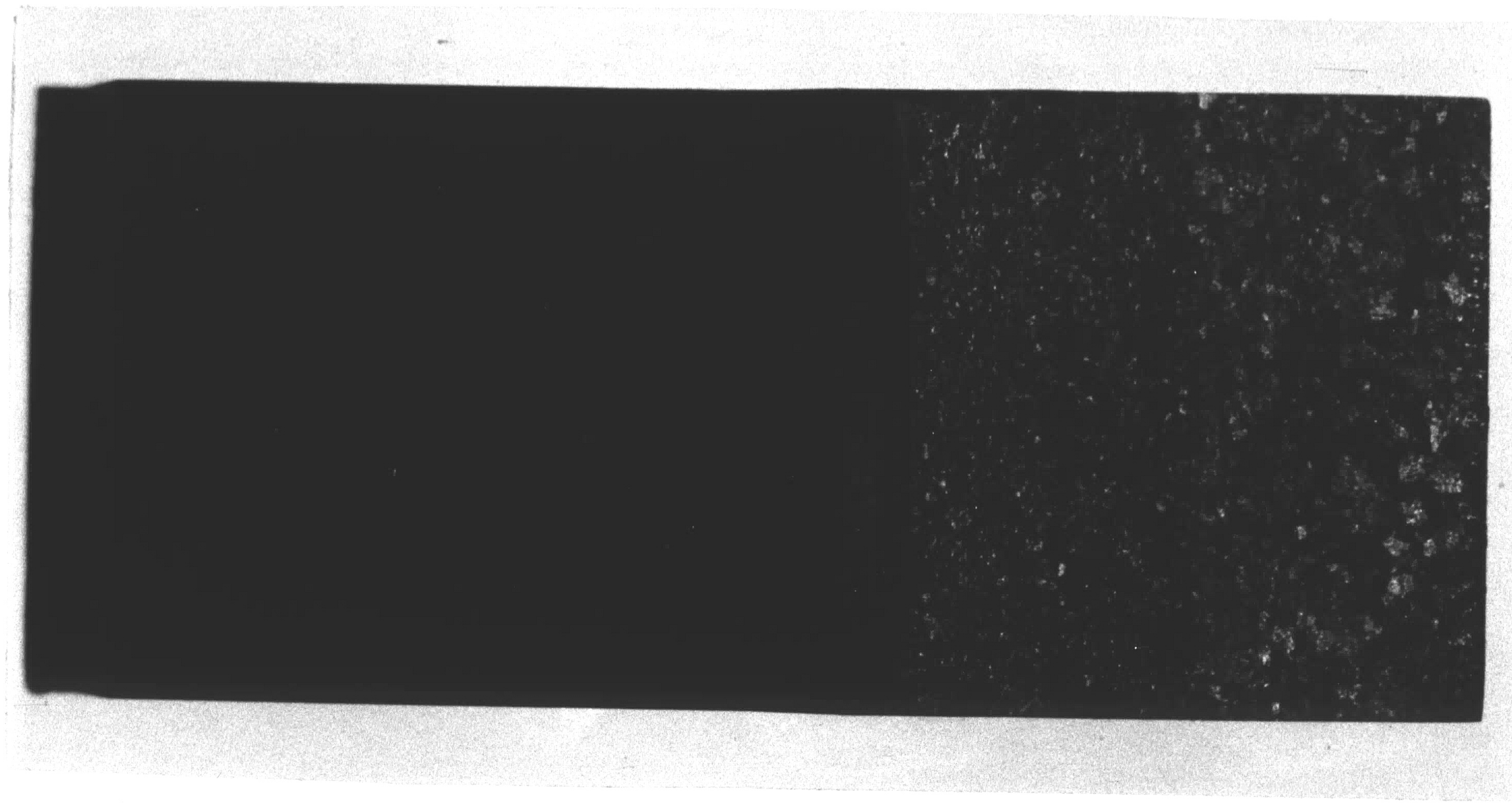
SAMPLE A20 — 300 X

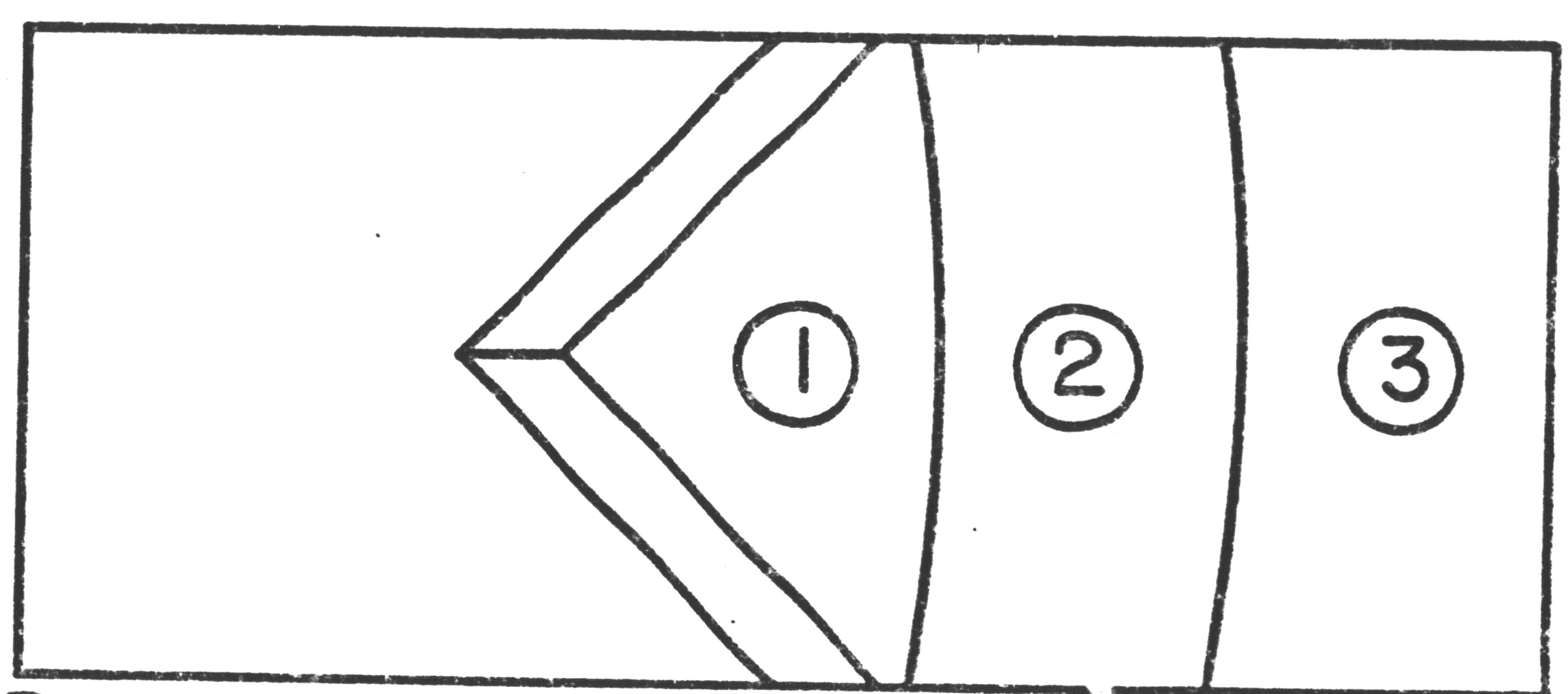
FIG. 13 - SEM OF THE CATASTROPHIC FRACTURE SURFACE OF AN Rc 46, H-11 STEEL SPECIMEN.

CRACK
PROPAGATION
→

SAMPLE A30 — 300 X

FIG. 14 - SEM OF THE CATASTROPHIC FRACTURE SURFACE OF AN Rc 56, H-11 STEEL SPECIMEN.





1 - CRACK GROWTH BY FATIGUE

2 - CRACK GROWTH BY STRESS CORROSION

3 - CATASTROPHIC FRACTURE

SAMPLE A30 — APPROXIMATELY 3.2 X
STEAM DISTILLED WATER ENVIRONMENT
INITIAL K_I LEVEL OF 71% OF ITS K_{IC}
TIME TO FAILURE = 163 MIN.

FIG. 15 - FRACTURE SURFACE OF AN Rc 56, H-11 STEEL SPECIMEN AFTER SUBCRITICAL CRACK GROWTH.

CRACK
PROPAGATION

SAMPLE A30 — 100 X

FIG. 16. - SEM OF FATIGUE CRACK SURFACE OF
AN Rc 56, H-11 STEEL SPECIMEN.

SAMPLE A30 — 100 X

FIG. 17 - SEM OF STRESS CORROSION CRACK SURFACE OF AN Rc 56, H-11 STEEL SPECIMEN.

TABLE 1 - FATIGUE CRACK DATA

Specimen No.	Average Hardness Rc	Angle of Chevron, Degrees	Chevron Notch Diameter, Inches	Applied Cycles at 130-2000 Lb. Load Range	Applied Cycles at 130-1300 Lb. Load Range
A04	56.1	36	.002	46,000	17,000
A05	55.8	37	.004	45,000	16,000
A06	56.1	36	.004	48,000	18,000
A11	46.7	36	.002	40,000	10,000
A12	46.4	37	.004	46,000	10,000
A13	46.5	36	.004	42,000	13,000
A14	46.4	38	.002	43,000	11,000
A15	46.3	36	.004	42,000	10,000
A16	46.6	36	.006	42,000	13,000
A18	56.4	38	.006	42,000	12,000
A19	55.8	37	.004	43,000	15,000
A20	46.4	37	.002	43,000	9,000
A22	55.5	38	.004	43,000	10,000
A23	55.0	38	.004	43,000	13,000
A25	56.5	36	.002	44,000	14,000
A26	56.1	37	.004	42,000	17,000
A27	55.3	37	.004	40,000	12,000
A30	56.6	37	.002	42,000	12,000
A31	55.7	37	.004	42,000	10,000

TABLE 2 - SPECIMEN DIMENSIONS

Specimen No.	Average Crack Length, a, Inches	Crack Length Due Only to Stress Corrosion Cracking, Inches	Width, B, Inches	Length, W, Inches	% Oblique
A04	.57502	.00587	.55931	1.12640	0
A05	.57326	0	.56013	1.12502	0
A06	.58152	0	.55934	1.12485	0
A11	.61466	0	.55925	1.13151	14.22
A12	.62064	0	.55789	1.12250	13.85
A13	.58581	0	.56034	1.12958	17.20
A14	.58998	0	.55930	1.13215	13.21
A15	.60604	0	.55824	1.12692	11.84
A16	.58304	0	.55946	1.12698	12.01
A18	.57643	.12691	.55985	1.12530	0
A19	.57463	0	.55865	1.13096	0
A20	.58503	0	.55692	1.13221	11.19
A22	.58429	.19730	.55948	1.12689	0
A23	.60241	0	.55969	1.13027	0
A25	.58530	0	.55890	1.12780	0
A26	.58358	0	.55985	1.12887	0
A27	.58069	.16488	.56081	1.12950	0
A30	.59964	.28038	.55971	1.12531	0
A31	.57444	.17599	.55910	1.12857	0

TABLE 3 - VALID K_{Ic} TESTS

Specimen No.	P_{max}, Lbs.	P_Q, Lbs.	Estimated Yield Strength, ksi	ASTM K_{Ic} Based on a - Actual, ksi$\sqrt{in.}$	K_{Ic} Based on a - Effective, ksi$\sqrt{in.}$	Percent Difference in K_{Ic}'s
			A. Rc 46			
A11	4248	4248	194.6	78.59	80.77	2.77
A12	3840	3840	194.0	73.89	75.77	2.54
A20	5154	5088	194.0	86.76	89.53	3.19
			B. Rc 56			
A05	1430	1430	243.0	23.79	23.82	.13
A06	1445	1445	244.5	24.63	24.67	.14

TABLE 4 - STRESS CORROSION CRACKING TESTS: NO SUBCRITICAL CRACK GROWTH

Specimen #	Environment	Estimated Yield Strength, ksi	Sustained Load, Lbs.	Initial K_I ksi$\sqrt{in}$	Time at Sustained Load, Min.	Failure Load, Lbs.	P_Q, Lbs.	ASTM K_{Ic} Based on a-Actual ksi$\sqrt{in}$	K_{Ic} Based on a-Effective, ksi$\sqrt{in}$	Percent Differences in K_{Ic}'s
A. Rc 46										
A13	H_2O	194.2	4000	68.27	1592	5130	5130	87.56	90.42	3.27
A16	H_2O	194.5	4520	77.05	1359	4850	4850	82.68	85.06	2.87
A15	H_2O	193.8	----	-----	0	4452	4452	81.20	83.61	2.96
A14	Oil	194.0	4540	78.15	1211	5220	5220	89.86	93.00	3.49
B. Rc 56										
A27	H_2O	240.2	690	11.60	4385	----	----	-----	-----	----
A27	H_2O	240.2	860	14.46	2751	----	----	-----	-----	----
A27	H_2O	240.2	1060	17.83	1330	----	----	-----	-----	----
A23	Air	239.3	1320	23.60	3971	1370	1370	24.50	24.54	.16
A19	Oil	243.0	1100	18.22	1583	1580	1580	26.17	26.21	.16
A26	Oil	244.5	1440	24.48	4270	1550	1550	26.35	26.40	.17
A25	Oil	246.5	1450	24.86	1410	1550	1550	26.57	26.62	.17

TABLE 5. - STRESS CORROSION CRACKING TESTS: SUBCRITICAL CRACK GROWTH

Specimen No.	Estimated Yield Strength ksi	Initial Load, Lbs.	Initial K_I, ksi$\sqrt{in}$	Estimated Propagation Time, Min.	Load at Failure, Lbs.	Change in COD Due Only to Stress Corrosion Cracking, 10^{-5} Inches	Estimated K_{Ic} ksi$\sqrt{in}$
			Rc 56	ENVIRONMENT: H_2O			
A30	247.0	1000	17.91	163.	535	540.	30.36
A22	241.5	1110	18.99	41.6	840	350.	29.32
A31	242.3	1205	20.02	54.6	865	320.	26.21
A27	240.2	1260	21.19	40.8	930	290.	27.44
A18	246.0	1270	21.31	40.3	1050	210.	26.55
A04	244.5	1375	22.96	.74	1375	0	23.33

TABLE 6 - STRESS CORROSION CRACK GROWTH FOR SPECIMEN A27

Propagation Time, Min.	Change in COD 10^{-5} inch	Calculated Change in Crack Length, Inch	Change in Applied Load, Lbs.	Applied K_I, Ksi$\sqrt{\text{in.}}$	Calculated Crack Growth Rate, da/dt 10^{-4} inch/min.
.74	0	.006	0	21.54	–
5.0	12.	.015	- 10	21.92	21.
10.0	27.	.028	- 30	22.39	26.
15.0	46.	.041	- 60	22.70	26.
20.0	70.	.056	- 80	23.38	30.
25.0	112.	.080	-130	24.21	48.
30.0	158.	.104	-180	25.15	48.
35.0	214.	.130	-240	26.17	52.
40.0	279.	.160	-320	27.18	60.
40.8	290.	.166	-330	27.57	75.

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VITA

Kenneth M. Kroupa was born on October 18, 1946, in Chicago, Illinois. He graduated from Morton Junior College in Cicero, Illinois, with an Associate of Arts degree in Engineering in 1966 and graduated with Honors from the University of Illinois with a Bachelor of Science degree in Mechanical Engineering in 1969. While at the University of Illinois, he gained membership in Tau Beta Pi and Sigma Tau, national honorary engineering fraternities and Pi Tau Sigma, national honorary mechanical engineering fraternity. In 1969 the author also obtained his Engineer-In-Training license in Illinois. Upon graduation he joined Western Electric Company, Inc. and has worked at various locations in Chicago, Illinois; Lisle, Illinois; and Princeton, New Jersey. In 1971 he entered the Graduate School of Lehigh University in the Metallurgy and Materials Science Department.